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How to cite:

Sargeant, H. M.; Abernethy, F.; Anand, M.; Barber, S. J.; Sheridan, S.; Wright, I. and Morse, A. (2020). Water production from lunar simulants and samples: an in situ resource utilization demonstration. In: 51st Lunar and Planetary Science Conference, 16-20 Mar 2020, The Woodlands, Texas (forthcoming).

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Version: Poster

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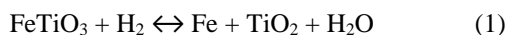
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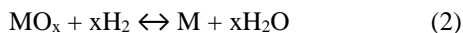
WATER PRODUCTION FROM LUNAR SIMULANTS AND SAMPLES: AN IN SITU RESOURCE UTILIZATION DEMONSTRATION H. M. Sargeant¹, F. Abernethy¹, M. Anand^{1,2}, S. J. Barber¹, S. Sheridan¹, I. Wright¹ and A. Morse¹. ¹School of Physical Sciences, The Open University, Walton Hall, Milton Keynes, UK. ²The Natural History Museum, London, UK. Email: hannah.sargeant@open.ac.uk

Introduction: Water is a critical resource for long term human exploration of the Moon and beyond as it can be used for life support supplies and for rocket propellant in the form of hydrogen and oxygen. Lunar polar water ice deposits could be harvested for such uses. However, these deposits may not be easily accessible from around stations where the water supplies are needed. Also, these ice deposits occur in permanently shadowed regions (PSRs) reaching temperatures of <30K, adding technological challenges for accessibility. Alternatively, water can be obtained from dry regolith by extracting the oxygen from the minerals and combining it with hydrogen [1]. A water production demonstration will be attempted by the ProSPA instrument which will be heading to a south polar region of the Moon in ~2025 on-board Luna-27 [2]. Although ProSPA is optimized to analyze volatiles in the lunar regolith, in this work we show how the instrument can also be used to perform one of the first in-situ resource utilization (ISRU) experiments on the Moon. We show how the simple system can successfully produce water from a lunar simulant, a lunar meteorite, and Apollo samples, and discuss the suitability of lunar simulant and meteorite as proxies for lunar material with regards to ISRU studies.

Proposed ISRU technique: Hydrogen can reduce iron-oxide-bearing minerals in an equilibrium reaction when heated to temperatures of at least 900°C [1]. The most easily reducible mineral on the Moon is ilmenite (FeTiO₃), and this is the most studied ISRU reduction process:



Other iron-oxide-bearing minerals such as pyroxene and olivine can also be reduced, albeit at lower efficiencies, as can other metal oxides such as those containing TiO₂, SiO₂, and MgO [3]. A generic formula for the reduction of any metal-oxide-bearing mineral can be written as:



where MO and M represent metal oxide and metal respectively.

The hydrogen reduction technique simply requires a furnace, hydrogen, and a method of removing the produced water from the gas phase so that the forward reaction can continue. Most proposed reactors utilize a flow of hydrogen gas which removes the produced water [4]. The ProSPA design includes a carousel of

ovens and an on-board supply of hydrogen, however a flow of gases cannot be obtained as it is a static system. Instead, ProSPA would use a cold finger to produce a temperature gradient that will remove any produced water from the gas phase and therefore allowing the reaction to continue [5].

Experimental procedure: Our previous work has shown that a static system can be used to reduce ilmenite to produce water [6]. A breadboard model (ISRU-BDM) was developed to replicate the key aspects of the ProSPA design (Fig. 1), and the experiment was optimized. Samples of ~45 mg, similar to those expected in the ProSPA ovens, were prepared. The samples we heated to 1000°C in the presence of ~420 mbar of hydrogen, while the cold finger was set to -80°C. The samples were reacted for 4 hours and the water was collected at the cold finger. Quantification of the reaction rate and yield were determined by pressure changes within the system.

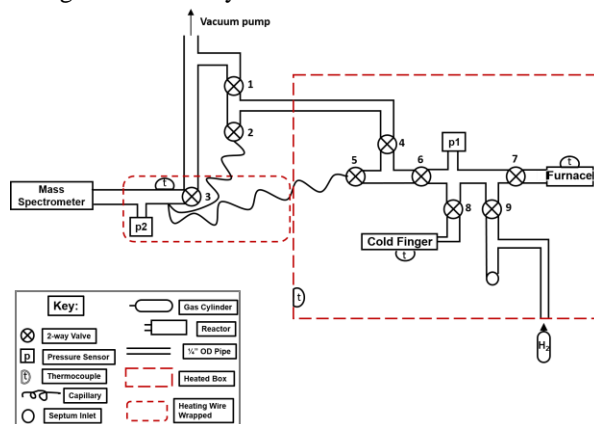


Fig. 1 ISRU-BDM schematic

Lunar simulant and samples: Four different materials were studied in this work. The lunar simulant selected is NU-LHT-2M, a highland simulant which contains 0.6 vol.% ilmenite [7]. The simulant was also doped with 10 wt.% ilmenite to replicate a more FeO-rich soil. Next, the reaction was performed on lunar material in the form of a crushed meteorite, Northwest Africa 12592, which is classified as a fragmental breccia and chosen as a representative of the bulk lunar regolith at feldspathic lunar highlands, albeit with no identifiable ilmenite [8]. To eliminate the effects of iron-oxide weathering products, some of the meteorite samples were treated with EATG which is commonly used to remove secondary iron-oxides [9]. The average

FeO content of NU-LHT-2M and NWA 12592 are to be determined in due course. Finally, two Apollo soil samples were selected: a mare soil, 10084, and a highland soil, 60500. The mare soil has a relatively high FeO content (~15.7 wt.%) and contains ilmenite [10], whilst the highlands soil has relatively low FeO content (~5.5 wt.%) with trace amounts of ilmenite [11]. To prevent any fines from passing through the filter on the ISRU-BDM, each sample was sieved prior to the experiments to remove grains <38 μm .

Results: Yields. After a 4 hour reaction, the water is released from the cold finger and the associated pressure rise was used to quantify the yield (Table 1), where a 1 σ uncertainty was derived from the three repeats for each experiment. The results for a pure ilmenite sample are also shown as taken from [6]. Mass spectra from the released vapor were analyzed which confirmed the composition of the product as water.

Table 1 Yields from the reduction of lunar simulant and samples, as compared to pure ilmenite

Sample	Average yield (wt.% O ₂)
Ilmenite	3.43±0.14
NU-LHT-2M	0.29±0.04
90% NU-LHT-2M: 10% ilmenite	0.89±0.04
NWA 12592 - treated	0.07±0.02
NWA 12592 - untreated	0.08±0.01
10084	0.94±0.03
60500	0.18±0.02

SEM analysis. Reacted and un-reacted samples of each material were set in epoxy resin and polished for analysis using the Scanning Electron Microscope (SEM). Back Scatter Electron (BSE) imaging was used to identify the reduction product, Fe, visible as bright white blebs, and therefore show how the reaction proceeds in each mineral type (Fig. 2). Where ilmenite is present, the mineral reduces significantly, producing large veins of iron. Other minerals such as olivine and pyroxene also show some evidence of reduction, dispersed with smaller iron-blebs. As anticipated, plagioclase showed little-to-no evidence of reduction.

Discussion: The static system is capable of reducing iron-oxide bearing minerals and can be used to measure quantitative yields of water. With increasing

ilmenite content, the yields increase, which is to be expected. A proportion of the iron-oxide in the highland simulant is in the form Fe₂O₃, which is not found in lunar material, but is highly reducible and may lead the highland simulant to give faster reaction rates/higher yields. The lowest yields were obtained from the meteorite which has no ilmenite, but reduction was evident in pyroxene and olivine, as was found in all other samples. Yields may also have been lower in the meteorite because the average grain size, a result of the manual crushing process, was larger than the lunar soil average resulting in a smaller surface area for the reaction. The sieving process applied to each sample has increased the average grain size and therefore yields are expected to be higher in un-sieved samples.

Conclusions: Lunar soil simulant, lunar meteorite, and Apollo soil samples that contain iron-oxide bearing minerals such as pyroxene and olivine, along with ilmenite, can be reduced in a static system. This reduction procedure could be implemented on any instrument suite exploring a planetary surface providing the three requisite components; furnace, cold finger, and hydrogen are on-board. The technique outlined in this work is recommended for use on small scale prospecting instruments as a proof-of-concept for early water production on the Moon without any restrictions on geographical location.

Acknowledgments: The funding by STFC of a studentship for H.S. is acknowledged. ProSPA is a programme of and funded by the European Space Agency (ESA).

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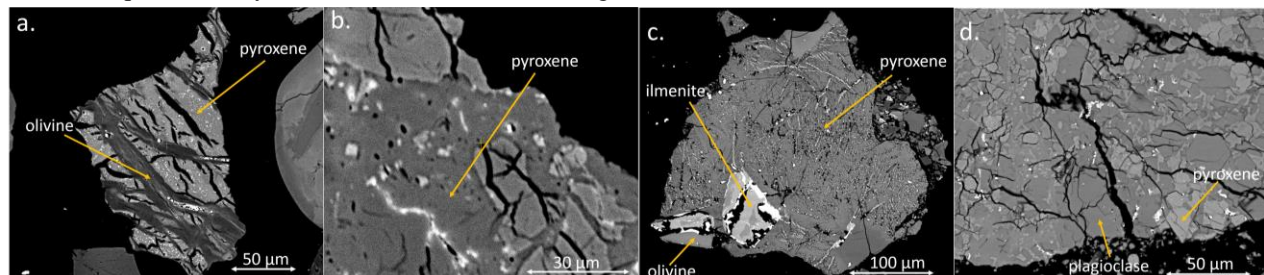


Fig. 2 Example BSE images from the reacted materials. Bright white blebs indicating Fe formation are identified in all samples. a.) NU-LHT-2M, b.) NWA12592, c.) 10084, and d.) 60500.